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While it is quite a familiar fact that the luminosity of any spectral ray increases proportionately to the heat in this ray, and indeed is but another manifestation of the same energy, I have recently had occasion to notice that there is, on the part of some physicists, a failure to recognize how totally different optical effects may be produced by one and the same amount of energy according to the wave-length in which this energy is exhibited.

I should not perhaps have thought it advisable to make this last remark, were it not that there has appeared in a recent number of Wiedemann's Annalen, a paper by H. F. Weber on "The Emission of Light," in which he tacitly makes the assumption that the luminosity of a color is proportionate to the energy which produces it, an assumption which it is surprising to find in a paper of such general merit and interest.

In another article of the same number of the journal, the mistake was pointed out by Professor F. Stenger, who remarked that Mr. Weber's assumption was inconsistent with the investigations of the present writer. Still the fact that there could be such a misapprehension at the present day, led me to look at the matter again, and to observe, with some surprise, that there was nowhere, in any physical work known to me, any exact or even approximately exact statement of the relative ocular effects of a given amount of energy in different parts of the spectrum. I have undertaken therefore during the last few months an experimental re-investigation of this subject, with such a statement especially in view.

We shall evidently need two correlated sets of experiments, the first set to determine the amount of energy in each ray, the second to show the corresponding visual effect.

For the first of these, since energy only shows itself through absorptive media which more or less disguise it, we must select that manifestation which disguises it least, and in this respect beyond comparison the thermal one stands first, as the *heat* dispersed by a glass prism and shown by a thickly lampblacked thermometric apparatus is, throughout the visible spectrum, very nearly proportionate to the energy itself. For these first or thermal experiments, whence the energy is readily deduced, with close approximation, we shall rely principally upon a very elaborate investigation made here some time since and already published, where the bolometer is used to deduce in terms of

* Read by abstract before National Academy of Sciences, April 19, 1888.

lampblack absorption the relative amounts of solar energy in various wave-lengths throughout the visible spectrum and a little beyond; and which has been supplemented by a new investigation of the same kind in the present connection.

Our second set of experiments will consist of a recent parallel series of photometric solar measures taken at the same wave-lengths as the thermal ones, and which we may say gives this energy in terms of what I may perhaps be allowed to call, provisionally, "retinal" absorption.

The thickly lamp-blacked surface, then, and the retinal screen provided by nature in the eye, both exercise selective absorption, but the first whose absolute absorption is here nearly total does so in relatively so small a degree, that we may, in the visible spectrum, provisionally neglect it, and consider the bolometric effect as here proportional to the energy itself.

It is evident that these two series once made, and reduced in both cases to the normal spectrum, would give us for any individual human eye the means of stating the visual effect in terms of absolute energy. The visual effect is known to vary in a very minute degree with the absolute amount of this energy, at least if we admit the physiological influence of what has been called "the color of brightness," but for the comparatively feeble lights employed, this physiological effect seems to be almost negligible, and it is nearly immaterial within the limits of the experiment what unit of energy we take.

The object of these experiments, then, is to take some one constant amount of energy, to actually or virtually display it successively in different portions of the spectrum, and to observe in what proportion the optical or visual effects of this fixed amount of energy vary, according to the wave-length in which it is conveyed. While the measurements which insure this constancy are best made by thermal methods, and while the prism is on the whole far more convenient for them than the grating, it is nevertheless desirable to reduce the whole measurements to what they would have been, if taken directly in the normal spectrum. The writer's measurements, already published and here cited later, afford the means of doing this with precision. These show that the energy is far from being distributed equally even in the normal spectrum; and that, accordingly as it varies from one part of the spectrum to another, we must, by opening the aperture through which it is admitted where it is weak, and by narrowing it where the energy is strong, or by other like device, maintain it absolutely constant, or else (what is far better) let it enter through one fixed aperture, and use the subjoined table to apply a correction for the actual irregularities. Let it be remembered that we are now speaking of absolute energy, not of those physiological effects of it on the organ of vision which we call light, and it is

to the value of this absolute energy for different wave-lengths in the normal spectrum which the subjoined table refers. This table, which gives the energy as derived from thermal experiments, rests on many thousand observations, taken, however, all with what is called a high sun, *i. e.*, with a sun more than 30° above the horizon. As the distribution of this energy varies somewhat from day to day, and particularly in the violet and beyond, we have supplemented it by a series of direct observations taken with the bolometer on April 6, 1888, using the same glass prism employed in the photometric work described later. As those observations show a fair accordance with the others, it is not necessary to repeat them.

TABLE I. NORMAL SPECTRUM.

$\lambda = 0^{\mu}{\cdot}35$	$0^{\mu}{\cdot}38$	$0^{\mu}{\cdot}40$	$0^{\mu}{\cdot}45$	$0^{\mu}{\cdot}50$	$0^{\mu}{\cdot}55$	$0^{\mu}{\cdot}60$	$0^{\mu}{\cdot}65$	$0^{\mu}{\cdot}70$	$0^{\mu}{\cdot}75$	$0^{\mu}{\cdot}768$
Heat= 1·8	3·7	5·3	11·9	17·3	20·7	21·9	22·2	21·4	20·7	20·2

What has just been given in table I refers to the distribution of energy in terms of lamp-black absorption, *i. e.*, as "*heat.*" We now proceed to attempt to find it in terms of retinal absorption, *i. e.*, as "*light.*" It is well known that color photometry offers peculiar difficulties. My own experience, after a long employment of the Rumford photometer for comparing the relative intensity of different colored lights, is most unfavorable to it, and I have also tried the Bunsen photometer with almost equally unsatisfactory results. I have also experimented with the ingenious photometer described by Masson (Ann. de Ch. et de Ph., ser. III, xiv, p. 129), in which a disk of paper, marked with black and white sectors, is revolved with such rapidity that it assumes a uniform tint when viewed by the colored light in question, but when illuminated by the electric flash displays the sectors again. It is evident that the reappearance of the sectors under the flash will be conditioned by the nature of the light which furnishes the steady illumination. But though on trial this has seemed to yield better results than the ordinary photometers, the method is of difficult application in connection with the particular apparatus about to be described. I have therefore, after considerable experiment, decided in favor of what may seem, at first, to be a cruder method, but which is, I believe, for the present purpose, preferable to any of the foregoing; I mean the determination of the intensity of light necessary to read a table of logarithms or to discern any arbitrary characters.

Description of the Apparatus.

The measures have all been made in a dark room from which every source of outside light is excluded except that which enters the slit of the spectroscope.

The light from the siderostat mirror, M (fig. 1) passes through a small aperture in the north wall and falls on the slit (s_1), (which has doubly moving jaws, 34^{mm} high, set in these experiments at a standard distance of $0{\cdot}1^{mm}$), then on the great collimating lens (l) of 755^{cm} focus (aperture $11{\cdot}9^{cm}$), t_1 being a paper tube to prevent the lateral diffusion of light from dust particles. p is a glass prism,* m, the concave mirror of 148^{cm} focus, which here forms upon a second slit (s_2) a spectrum about 7^{mm} high and 90^{mm} long in the easily visible part from A to H. The prism and mirror are mounted on the spectro-bolometer already elsewhere described,† and which is provided with a circle reading to 10″ of arc. By setting this circle, any color can be brought on the slit (s_2). The light which the mirror has converged into that part of the spectrum overlying this slit passes through it, diverges and falls upon a black paper, figure 2, in which is a central aperture 1^{cm} square, occupied by part of a table of logarithms, printed in small black type on white paper. This table can be adjusted to bring different figures in view, but is otherwise fixed relatively to the black paper screen which (with this central centimeter occupied by figures) is mounted on a slider. The rod (r) on which the slider moves is a prolongation of the spectroscope arm, made of a light wooden rod graduated so that one can read the position of the slider to a centimeter by *feeling* of notches in the dark. The zero of this rod is at slit 2 on which the spectrum is thrown.

It is to be observed that it is necessary that the square of figures should be small in order that it may be slid nearly to the apex of the cone of light and remain covered thereby.

It is to be noted also that at a constant distance and in a feeble light, these small figures may be invisible to the naked eye and most distinctly visible to the same eye with a magnifying glass. For two eyes of different foci, the amount of light with which the same figures will be read will probably vary. It follows that even if the same person read from beginning to end of the series, his readings will not be com-

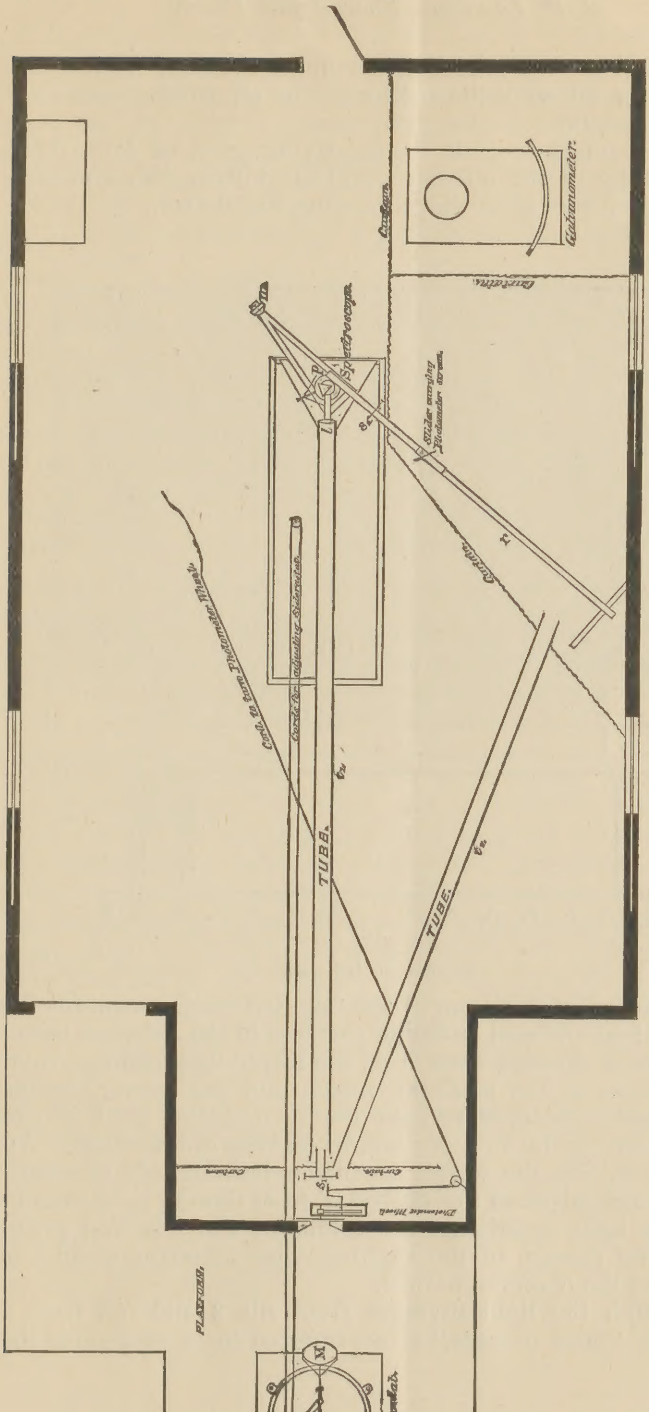
* Its principal constants are: height of face $11{\cdot}5^{cm}$, width, $10{\cdot}5^{cm}$, while for a temperature of 28° C. the refracting angle is 60° 06′ 45″, deviation

$$\begin{aligned} H &= 46°\,45'\,35'' \\ b_1 &= 44\ \ 45\ \ 55 \\ D_2 &= 44\ \ 11\ \ 15 \\ A &= 43\ \ 24\ \ 05 \end{aligned}$$

ω_2 ("little Omega") = 41 34.

† "Researches on Solar Heat," Prof. Papers of the Sig. Serv., No. 15, p. 130.

1.

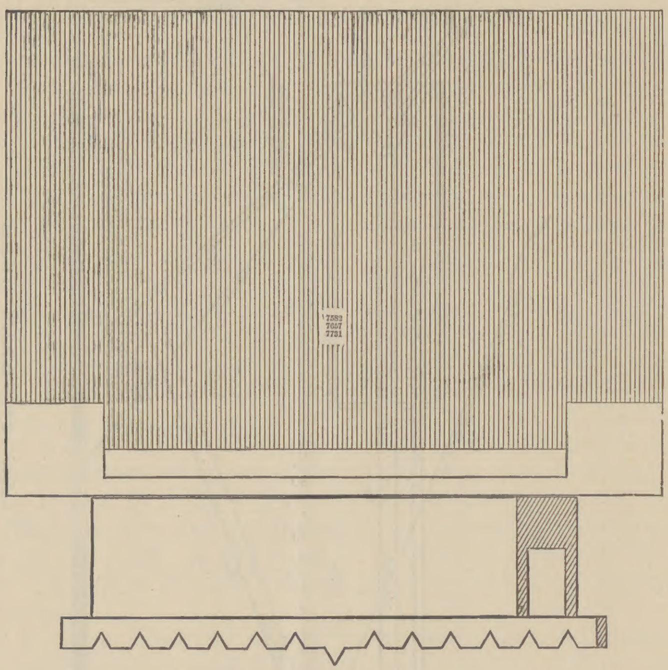


PLAN OF DARK-ROOM.

parable unless they are all taken under the same optical conditions, e. g. all with the naked eye or all with glasses of a certain strength.

In these measurements a magnifying glass of $4{\cdot}7^{cm}$ focus was used by all the observers, and in addition, two who were near-sighted wore spectacles correcting this defect.

2.



Screen, one-half size.

The observer, in a room completely darkened, except for the minute light diffused from the particles in the reflected beam, and himself shielded even from the feeble light diffused from the surfaces of the lens, the prism, and the mirror, by the thick black curtain shown on the plan, waited until his eye had become quite sensitive before making the readings. An assistant outside the curtain set the circle by the aid of a dark lantern, and adjusted the siderostat from time to time so as to keep the light exactly on the center of the lens and prism face. The passage of the slightest wisp of cirrus cloud was noted and the observer warned.

Although the light diverges from slit 2 and not from a point, the "cone of rays," above referred to, is, as regards the

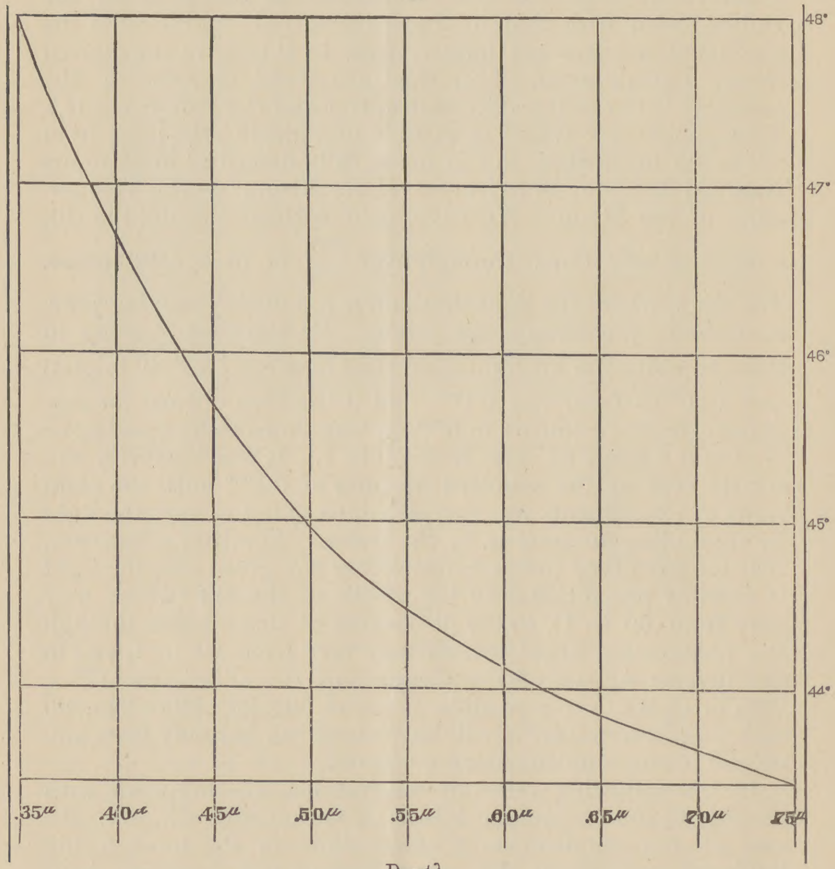
object and limits of our experiments and the limiting positions of the screen, so nearly coincident with a geometrical cone, that, as the slider is carried away from the slit, the light may be treated as diminishing proportionally to the inverse square of the distance from the slit to the screen. The nearest position of the screen brings it within 20^{cm} of the slit, the farthest is over 300, so that we have the power of diminishing the light over $\left(\frac{300}{20}\right)^2$ or over 225 times. This however is by no means a sufficient range for the comparison of the light in the yellow green with that in the extreme red; and because the graduated rod was not long enough to thus give the desired range, a photometer wheel was introduced in some of the measures between the siderostat mirror and the remote slit (s_1). This photometer wheel is capable of reducing the light from ·50 to ·05 or further, and is more fully described in Memoirs National Academy of Sciences, vol. iii, Memoir on the Temperature of the Moon. We have, then, without altering the slit, a range of adjustment through over $\frac{\cdot 225}{\cdot 05}$ or over 4500 times. The slit s_1 where the light first enters has doubly moving jaws, controlled by a micrometer screw. Its standard opening in these experiments for light comprised between $\lambda = 0^{\mu}\cdot 40$ (violet) and $\lambda = 0^{\mu}\cdot 65$ (red) was $0\cdot 1^{mm}$, but it has been opened for supplementary experiments to 5^{mm}, so that we have by opening or closing it a range of light from 50 to 1. It was, however, constantly kept at the standard opening of $0\cdot 1^{mm}$ until the main series of experiments was completed, so as not to vary the light by attempting to reset it by the screw. Admitting, however, that for any given prism, transmitting any given ray, the light is sensibly proportional to the width of the slit (which may vary from 50 to 1), to the disposition of that coming through the photometer wheel, which may vary from 20 to 1, and to the inverse square of the distance of the slider from slit s_2 (225 to 1), we have a possible range of $50 \times 20 \times 225 = 225{,}000$ to 1. This, however, it will be understood, has only been employed in our supplementary measures.

In the following table all observations, whether made with or without the photometer wheel, or with a wide slit, as in the case of the supplementary observations in the most feebly luminous portions at the extremities in the spectrum, have been reduced to these standard conditions:

Photometer wheel absent;
Slit (s_1) $0\cdot 1^{mm}$ wide;
Slit (s_2) 1^{mm} wide;
Slider with logarithm table at 1 meter from slit s_2.

Each reading of the logarithms in the slider is taken when certain figures become discernible in the light in question, and is the mean of three independent observations, taken consecutively. In order to find the wave-length by means of the prism we must prepare a table or a graphic construction, deduced from an examination of the special prism employed, showing the wave-length corresponding to the position of mini-

3.



$D = \phi\lambda.$

mum deviation of each ray. Figure 3 is such a graphic construction derived from our own observations of the constants of the prism employed, and Table II gives the approximate values of the tangents to the curve by means of which we pass from the prismatic to the normal scale.

TABLE II.

Approximate deviations and reducing factors (tangents) corresponding to adopted wave-lengths for great Hilger prism.

Wave-lengths. μ	Adopted Tangents to curve.	Deviations.
·35	2·28	48°00′
·38	1·94	47 10
·40	1·73	46 42
·45	1·27	45 42
·50	·88	44 58
·55	·62	44 28
·60	·46	44 07
·65	·36	43 50
·70	·30	43 38
·75	·27	43 26
·768	·26	43 22

TABLE III.

Co-efficients of reflections from two surfaces of silver.

Wave-lengths	·35	·38	·40	·45	·50	·55	·60	·65	·70	·75
Percentage reflected from two surfaces ---	·37	·54	·63	·73	·79	·82	·845	·86	·875	·885
Reduction factor (reciprocal)	2·70	1·85	1·59	1·37	1·27	1·22	1·18	1·16	1·14	1·13

Table III is a table for the selective absorption of silver referred to such a lamina as is spread by the Martin process on the front surface of the glass in its ordinary application. It is prepared from unpublished observations made by the writer with the bolometer in the course of the year 1881, and for the method of its preparation the reader is referred to the foot note.* It will be seen from this table that while such a silver film exercises a considerable selective absorption in the ultra violet and even at the blue end, it exercises less as the wave-length increases, and in fact an extension of it would show a still enhanced power of reflection for infra-red rays. It is with these infra-red rays that our measures in previous researches on radiant heat at this observatory have been hitherto mainly made. Accordingly our measures of the selective reflection in the ultra violet, to which we have given comparatively little study, have not been repeated with all the care which the subject deserves, and we recommend a more complete determination

* The selective absorption of silver has been deduced by bolometric measurements in the solar spectrum, with a Rutherfurd grating, by producing multiplied successive reflections of the light from silver before allowing it to enter the slit of the spectroscope and determining successively the variation in the intensity of different rays according to the number of reflections. The observations are reduced by a logarithmic formula.

of the selective absorption of silver there as an interesting field still open for experiment to those engaged in the study of that end of the spectrum.

By means of this graphic construction, which is amply accurate for the immediate purpose, and by the use of the formula already described (Memoirs of the National Academy, vol. ii, p. 161), we can also pass from the actually observed prismatic spectrum to the effect which would have been observed in a truly normal one; and it is by the use of these constructions, founded on these formulæ, that the final reductions here given have been obtained. It is here assumed that no sensible selective absorption is exerted by the prism or any other portion of the apparatus.

We now give a summary of the photometric observations. The state of sky for each series and the approximate air masses were:—

March 30th.—Sky "fair blue;" observer, S. P. L.; time, $11^h\ 40^m$ A. M. to $12^h\ 45^m$ P. M. (Greenwich 5th hour meridian time); air mass,* 1·22 atmospheres.

April 2d.—Sky "milky blue with cumuli;" observer, F. W. V.; time 12^h to 2^h P. M.; air mass, 1·19 atmospheres.

April 3d.—Sky "blue with cumuli," better than on 2d, sky better in E. M.'s series than in that of F. W. V., when a slight haze, barely perceptible, had formed.

1st series; observer, E. M.; time, $11^h\ 10^m$ A. M. to $12^h\ 30^m$ P. M.; air mass, 1·18 atmospheres.

2d series; observer, F. W. V.; time, $1^h\ 15^m$ to $2^h\ 30^m$ P. M.; air mass, 1·28 atmospheres.

April 4th.—"A good blue at first, after 12^h milky blue from slight smoke, but still a fairly good sky."

1st series; observer, F. W. V.; time, $10^h\ 25^m$ to $11^h\ 55^m$ A. M.; air mass, 1·23 atmospheres.

2d series; observer, E. M.; time, $12^a\ 30^m$ to $1^h\ 30^m$ P. M.; air mass, 1·20 atmospheres.

April 6th.—Sky "good blue, quite clear;" observer, F. W. V.; time, $10^h\ 45^m$ A. M. to $12^h\ 15^m$ P. M.; air mass, 1·18 atmospheres.

June 16th.—Sky "clear, good blue; after 1 P. M. cirrus streaks. Observer, B. E. L.; time, $11^h\ 15^m$ A. M. to $1^h\ 45^m$ P. M.; air mass, 1·05 atmospheres.

July 2d.—Sky "clear, excellent;" observer, B. E. L.

1st series; time, $11^h\ 25^m$ A. M. to $12^h\ 15^m$ P. M.; air mass, 1.03 atmospheres.

2d series; time, $12^h\ 15^m$ P. M. to $1^h\ 25^m$ P. M.; air mass, 1·02 atmospheres.

* By air mass is here meant that actually traversed by the solar rays, that with a vertical sun at sea level being unity.

We first give, in table IV, the values of the photometric measures in the prismatic spectrum, reduced to the standard conditions above cited.

TABLE IV.

Showing sensitiveness of the eye to light, as deduced from the power to decipher fine print.
Prismatic (uncorrected) values.

	$\lambda=0^{\mu}$·35	0^{μ}·38	0^{μ}·40	0^{μ}·45	0^{μ}·50	0^{μ}·55	0^{μ}·60	0^{μ}·65	0^{μ}·70	0^{μ}·75	0^{μ}·768
S. P. L.											
Mar. 30				0·29	3·01	19·31	19·15	3·88	0·28		
F. W. V.											
April 2			0·13	9·89	57·94	113·3	15·14	1·06	0·27		
April 3			0·30	9·88	154·2	167·9	26·91	1·99	0·43		
April 4			0·20	10·88	154·6	193·8	24·62	2·23	0·33		
April 6	0·0015*	0·017*	0·17*					2·32		0·005*	0·0012*
Mean	0·0015	0·017	0·20	10·25	122·25	158·33	22·22	1·90	0·34	0·005	0·0012
B. E. L.											
June 16			0·24	30·60	157·2	217·0	36·98	3·39	0·17	0·001*	
July 2	0·000*	0.003*	0·23	10·89	125·7	142·3	33·96	4·54	0·73	0·004*	
July 2			0·34	35·38	186·1	158·7	70·16	5·98	0·75		
Mean	0·000	0·000	0·27	25·62	156·3	172·7	47·03	4·64	0·55	0·002	
E. M.											
April 3			0·35	30·60	100·1	146·1	49·82	5·85	1·46		
April 4			0·19	8·34	46·39	75·27	42·05	3·04			
Mean			0·27	19·47	73·25	110·69	45·94	5·45	1·46		

* Blue (cobalt) glass over slit s_1.

In table V are the final values, corrected for loss of light by reflection from silver surfaces and reduced to the normal spectrum.

TABLE V.

Photometric values. Normal Spectrum.

	$\lambda=0^{\mu}$·35	0^{μ}·38	0^{μ}·40	0^{μ}·45	0^{μ}·50	0^{μ}·55	0^{μ}·60	0^{μ}·65	0^{μ}·70	0^{μ}·75	0^{μ}·768
S. P. L.											
Mar. 30				0·50	3·36	14·61	10 40	1·62	0·096		
F. W. V.											
April 2			0·36	17·21	64.76	85·69	8·22	0·44	0·092		
April 3			0·81	17·18	172·4	127·0	14·61	0·83	0·15		
April 4			0·56	19·11	172·8	146·7	13·37	0·93	0·11		
April 6	0·0092*	0·062*	0·47*					0·97		0·0015*	0·0003*
Mean	0·0092	0·062	0·55	17·83	136·65	119·8	12·07	0·79	0·117	0·0011	0·0003
B. E. L.											
June 16			0·65	53·23	175·7	164·2	20·07	1·42	0·058	·0003*	
July 2	0·000*	0·011*	0·63	18·95	140·5	107·6	18·44	1·90	0·25	·0012*	
July 2			0·94	61·56	208·0	120·0	38·09	2·50	0·26		
Mean	0·000	0·011	0·74	44·58	174·7	130·6	25·53	1·97	0·189	·0008	
E. M.											
April 3			0·95	53·23	111·9	119·5	27·05	2·44	0·50		
April 4			0·52	14·51	51·84	56·94	22·82	1·27			
Mean			0·74	33·87	81·87	83·72	24·94	1·86	0·50		

* Blue (cobalt) glass over slit (s_1).

In this table we have first, the wave-lengths corresponding to the observed angles of deviation, these values reaching from $0^{\mu}\cdot35$ in the ultra-violet to $0^{\mu}\cdot77$ near Fraunhofer's A on the extreme border of the visible red. It is to be observed, however, that the great mass of the observations which were taken without disturbing the slit reach from $0^{\mu}\cdot40$ in the deep violet to $0^{\mu}\cdot70$ in the deep red. The figures corresponding to $0^{\mu}\cdot35$, $0^{\mu}\cdot38$, $0^{\mu}\cdot75$, $0^{\mu}\cdot77$ are extremely difficult to obtain with precision and are given here as supplementary to the others. There are four observers :—

S. P. L., whose eye is somewhat long-sighted (making convenient the use of convex glasses of $\frac{1}{2}$ meter focus) and not sensitive to very feeble light; eyes otherwise believed to be in normal condition.

F. W. V., near-sighted, using glasses whose negative focus is 14^{cm}. The eye appears to be much less sensitive to the red than to the violet. The retina of this eye is somewhat deficient in black pigment.

B. E. L., near-sighted, using glasses whose negative focus is 42^{cm}.

E. M., a boy of fifteen whose sight is perfect as far as known.

It will be remembered that throughout this table from $0^{\mu}\cdot40$ to $0^{\mu}\cdot70$ the light enters through a slit whose aperture is constant. If under these conditions the logarithm table can be just read when the slider is one meter from the second slit (s_2), the light would be represented by unity; if at two meters, by 4; if at three meters, by 9; and so on. As, however, we have already explained, the length of the red being limited to but little over three meters, for the higher values we are obliged to introduce the photometer wheel. For instance, the strongest light observed by F. W. V. was in the prismatic yellow-green corresponding to a wave-length of $0^{\mu}\cdot55$ where 193·8 was noted. Had the rod been really indefinitely prolongable, the slider would have needed to have been removed to the length of nearly 14 meters. To avoid this the photometer wheel was interposed, reducing the light to $\frac{1}{20}$ and the actual distance of the slider from the slit (s_2) was, as we may easily see, $\sqrt{\frac{193\cdot8}{20}}$ or 3·11 meters. The feeblest light which has been here measured with the standard slit is that by F. W. V. on April 2d at wave-length $0^{\mu}\cdot40$ which is put down at 0·13 corresponding to a distance of 36^{cm} from slit (s_2).

To make clear the way in which we pass from table IV to table V, let us take any particular observation, for instance that already cited of April 4th by F. W. V. at $0^{\mu}\cdot55$, of 193·8. Referring either to the graphic construction, or to table I, we find the value of the tangent (at $\lambda = 0^{\mu}\cdot55$) $= 0\cdot62$ approximately, and $193\cdot8 \times \cdot62 = 120\cdot16$. Our table shows the reduction factor for two surfaces of silver to be 1·22, whence the final reduced value becomes

$$1\cdot22 \times 120\cdot16 = 146\cdot6$$

And in this manner from tables II and III the remaining values in table V are derived from those in IV; but here let it be observed that these values in table V do not yet represent what we wish, since they do not correspond in any exact sense to one constant amount of energy. It is true that they might at first sight appear to do so, since one constant quantity of solar energy actually or virtually entered through the same constant width of the slit to produce them, and passed through one constant aperture at the second slit, and since finally the prismatic values are reduced to these in the normal spectrum; but, as the writer has shown not only by theoretical deductions from what is observed with the prism, but by very numerous measures in the normal spectrum from a grating by means of a bolometer, the solar energy in the normal spectrum itself is very unequally distributed. (See table I.)

Since thermal and luminous effects vary proportionately in the same ray, it is to be observed that the values in table I furnish for each wave-length a divisor which gives not only the heat but the *brightness* which would have been observed had the prism dispersed the energy which fell on it in such a way that the same amount of energy fell in one part of the spectrum as in another, and thus we finally obtain the values in table VI

TABLE VI.

Sensitiveness of the eye for a constant amount of energy of varying wave-length.

$\lambda=$	$0^{\mu}\cdot34$	$0^{\mu}\cdot38$	$0^{\mu}\cdot40$	$0^{\mu}\cdot45$	$0^{\mu}\cdot50$	$0^{\mu}\cdot55$	$0^{\mu}\cdot60$	$0^{\mu}\cdot65$	$0^{\mu}\cdot70$	$0^{\mu}\cdot75$	$0^{\mu}\cdot768$
S. P. L.				0·042	0·194	0·706	0·475	0·073	0·004		
F. W. V.	0·0051	0·0168	0·104	1 50	7·90	5·79	0·551	0·036	0·005	0·00007	0·00001
B. E. L.	0·000	0·0030	0·139	3·75	10·10	6·31	1·17	0·089	0·009	0·00004	
E. M.			0·140	2·85	4·73	4·04	1·14	0·084	0·023		
Mean*	*0·0026*	*0·0149*	*0·128*	*2·70*	*7·58*	*5·38*	*0·954*	*0·070*	*0·012*	*0·00006*	*0·00001*

* The observations of S. P. L. are here omitted from the mean.

It will be observed that no correction has been introduced for selective absorption in the substance of the prism itself, as this is absolutely negligible within the limited range of the spectrum we are discussing.

This table exhibits the relative effect upon very different eyes of a given amount of energy in the form of radiation of various wave-lengths.

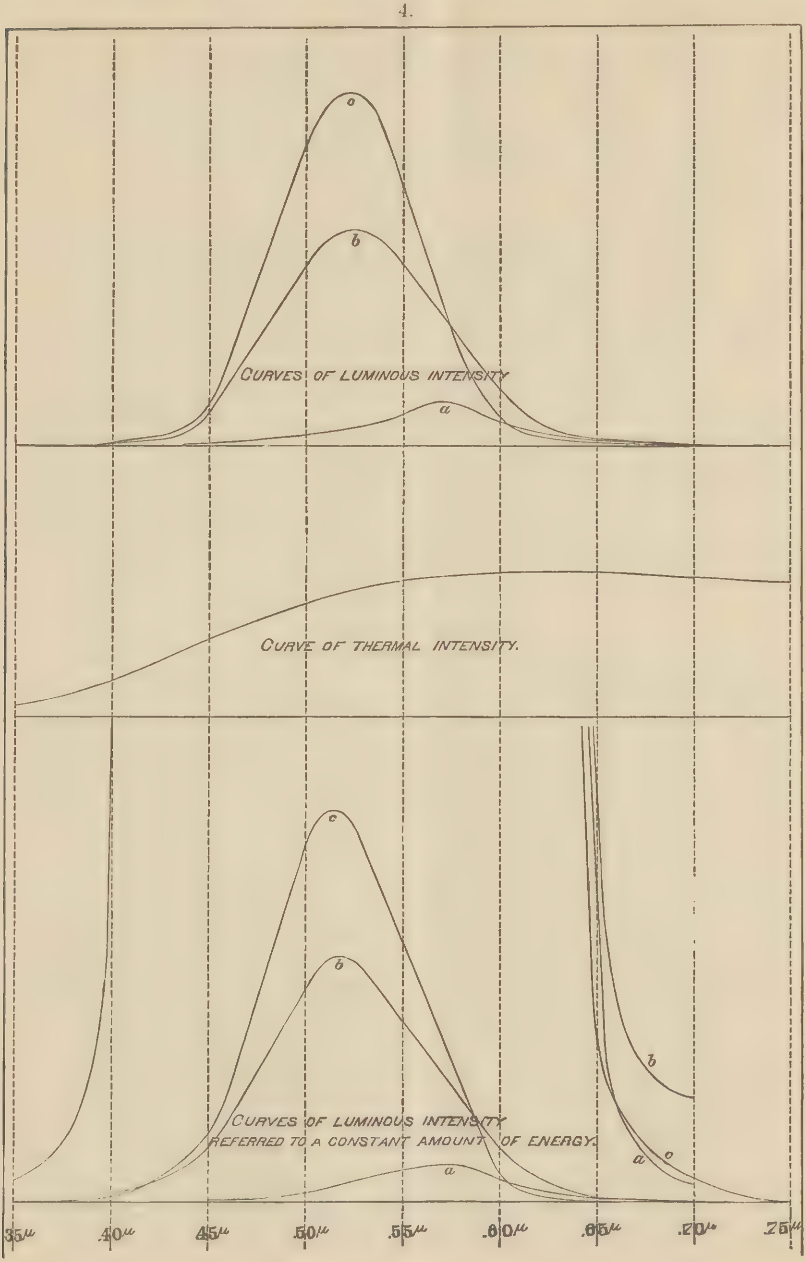
Quite notable differences exist between the different observers, not only as to the absolute sensitiveness of the eye, but also as to the relative efficiency for different colors. This seems to be, to some extent, a function of the age of the observer, if we may draw any conclusion from so few comparisons, the younger eyes being much more sensitive to the rays of shorter wave-length. Beyond this, any unusual efficiency for a particular part of the spectrum is perhaps apt to be balanced by a deficiency in another part, which, if strongly pronounced, would be termed color blindness. Prof. J. Clerk-Maxwell, employing pure spectrum colors, formed white by combining 26·3 per cent of red with 30·2 per cent of green and 43·5 per cent of blue (Phil. Trans. R. Soc., 1860, p. 79) and on another occasion with a slightly different apparatus (loc. cit. p. 74) the same observer made white by mingling 21·9 per cent of red with 33·3 per cent of green and 44·8 per cent of blue. The Allegheny observers, F. W. V., B. E. L., and E. M., with whom this experiment was repeated, required from one-fourth to one-tenth less red and one-sixth to one-eighth more blue than Maxwell, forming white by mingling 20 per cent of red with 30 per cent of green and 50 per cent of blue. Since, in order to make white, more of that color is required for which the eye is most sensitive, we may perhaps infer that Prof. Maxwell was somewhat less sensitive to blue than these observers, although it should be remembered that the relative intensity of the blue and red in the solar spectrum is liable to undergo considerable fluctuations, so that where direct comparison of individual eyes is impossible, some uncertainty must remain.

We have selected for comparison with our results the following by Capt. Abney (using a different photometric method), which we have here reduced to the normal scale. (See "Transmission of Sunlight through the Earth's atmosphere," by Capt. W. de W. Abney, R.E., F.R.S.; Phil. Trans. R. Soc., vol. 178, (1887), A., pp. 274–276). From the mean of the observations of July 1st, July 5th and July 21st, 1886, made with an average air-mass of 1·33 atmospheres, we obtain these photometric values for the normal spectrum:

$\lambda=$	$0^{\mu}{\cdot}40$	$0^{\mu}{\cdot}45$	$0^{\mu}{\cdot}50$	$0^{\mu}{\cdot}55$	$0^{\mu}{\cdot}60$	$0^{\mu}{\cdot}65$	$0^{\mu}{\cdot}70$
Light=	0·8	2·8	25·0	82·0	66·5	12·3	0·5

The general form of this curve agrees with that of S. P. L. (curve *a*, fig. 4), showing a maximum sensitiveness near $\lambda = 0^{\mu}\cdot 57$.

4.



The light curves of F. W. V. (curve *c*, fig. 4), and of E. M., (curve *b*, fig. 4), have their maxima respectively near $\lambda=0^{\mu}\cdot 52$ and $\lambda=0^{\mu}\cdot 53$.

Everything which has preceded has had reference to the *relative* luminous effects produced by *any* (moderate) constant quantity of energy. It may, however, be interesting to make the novel calculation as to the actual amount of energy either in horse power or any other unit required to make us *see*, and we can obtain an approximate estimate of this amount of energy as follows:

Actinometric measurements, made during the progress of the photometric observations, showed a solar radiation of 1·5 calories per square centimeter per minute. Of this amount of heat the slit (s_1), being $3^{cm}\cdot 4$ high by $0^{cm}\cdot 01$ wide, received the fraction 0·034. The visible spectrum from A to H, included, according to the bolometer measures, about 21 per cent of the total energy, the absorption of the lower infra-red by the great thickness of glass in the prism being large. We estimate that nearly 20 per cent had been lost by reflection before the bolometer was reached. The spectrum formed had a length of 86^{mm} from A to H. The *average* energy which passed through the millimeter aperture of slit s_2 was therefore (within these limits and expressed as heat),

$$1^{cal}\cdot 5\times 0\cdot 034\times 0\cdot 21\times 0\cdot 8\times\frac{1}{86},$$

or approximately $\frac{1}{10000}$ calorie, let us say 4,000 ergs per minute.

At 1 meter from slit s_2, this energy is further spread out over an illuminated area of 28 sq. cm., of which the square centimeter of fine print, being placed at an angle of 45° with the path of the ray, occupies only about $\frac{1}{40}$. If a length of 1^{mm} of the standard spectrum receives an average energy of $\frac{1}{10000}$ calorie per minute, the actual working part of the screen, consisting of the little square of fine print, will receive at a distance of 1 meter $\frac{1}{400000}$ calorie per minute. But this by no means gives the amount of energy requisite to produce vision, since the eye is able to receive a distinct visual impression in less than one-half second of time. We may say, therefore, that a luminous energy of $\frac{1}{50000000}$ calorie is sufficient to give a distinct view of the small square of figures in the brightest part of the spectrum, even after the immense loss of light by absorption and diffusion in the paper, which may amount to $\frac{19}{20}$ of the whole.

Even less light is needed to give the bare impression of luminosity. The sensitiveness of the human eye is indeed so extraordinary, that the chief difficulty in measuring its power is to find means for sufficiently reducing the intensity of sunlight,

which are at the same time capable of even approximate numerical estimation. Out of numerous plans tried, the following has given the most reliable result.

In front of the first slit, in the path of the rays from the siderostat, was placed a plate of glass very lightly smoked whose transmission for different kinds of light was first photometrically measured and found to be

For	violet light	($\lambda = 0^{\mu}\cdot 40$)	transmission	0·000210
"	green "	($\lambda = 0^{\mu}\cdot 55$)	"	0·000655
"	red "	($\lambda = 0^{\mu}\cdot 65$)	"	0·002350

The photometer wheel was next interposed, its aperture being sometimes reduced until only 2 per cent of the light received passed through it.

The slit was at first kept as near the standard width of $0\cdot 1^{mm}$ as possible; but it was afterwards deemed best to secure the final adjustment for the *minimum visibile* at the slit, as it was evident on trial that the inaccuracy due to the varying loss by diffraction was small, compared with the inevitable uncertainty of the observer himself.

Finally, the larger part of the necessary reduction was secured by reducing the aperture of the collimating lens by means of a metal plate pierced by a minute aperture whose area, $0\cdot 00015^{sq\ cm}$, was 0·000003 of the fully illuminated area of the lens.

The aperture of the human eye, according to du Bois-Reymond's photograph (see Nature, May 3, 1888, p. 15), is about $0\cdot 7^{sq\ cm}$, when fully expanded, or the same as that of the foreshortened disk of figures previously employed. The size of the light spot at the standard distance beyond slit s_2, when the minute aperture is placed over the collimating lens, is reduced so that about two-thirds of the light enters the eye placed 1 meter behind the 1^{mm} slit on which the spectrum is formed.

The following reductions of sunlight were needed in order to give a light which approximated to the *minimum visibile*, defining this to be, not the smallest light whose existence it is possible to suspect, or even to be reasonably certain of, but a light which is observed to vanish and reappear when silently occulted and restored by an assistant without the observer's knowledge.

Referred to the standard spectrum employed in the previous photometric work, the observer F. W. V. found:

Fraction of standard* violet light ($\lambda = 0^{\mu}\cdot 40$) required for certain vision $= 0\cdot 00021 \times 100 \times 0\cdot 000003 = 0\cdot 000000{,}063$.

* By "standard" is here meant the light in 1^{mm} of the standard spectrum, whose length from A to H was 86^{mm}.

Fraction of standard green light ($\lambda = 0^{\mu}\cdot 55$) required for certain vision $= 0\cdot 000655 \times 0\cdot 033 \times 0\cdot 000003 = 0\cdot 000000,0000655$.

Fraction of standard scarlet light ($\lambda = 0^{\mu}\cdot 65$) required for certain vision $= 0\cdot 00235 \times 2\cdot \times 0\cdot 000003 = 0\cdot 000000,0141$.

Fraction of standard crimson light ($\lambda = 0^{\mu}\cdot 75$) required for certain vision $= 10\cdot \times 0\cdot 000003 = 0\cdot 00003$.

The measures were made on July 3d and 11th, the sky being a fairly good milky blue and the sun within one hour of the meridian.

Assuming that the energy per millimeter of the standard spectrum was 0·000001 calorie per half second for the wave-lengths $0^{\mu}\cdot 55$ and $0^{\mu}\cdot 75$, we have from table I:

For $\lambda = 0^{\mu}\cdot 40$, energy $= 5\cdot 3 \div (20\cdot 7 \times 1,000000)$ calorie.
" $\lambda = 0^{\mu}\cdot 65$, " $= 22\cdot 2 \div (20\cdot 7 \times 1,000000)$ "

by means of which, we reduce each of the above values to absolute measure, obtaining for the maximum value of the

Minimum Visibile.

		Reciprocal of			Reciprocal of	
Violet	$0^{\mu}\cdot 40$	63,000000,000000	calories	=	1,500000	ergs.
Green	$0^{\mu}\cdot 55$	15000,000000,000000	"	=	360,000000	"
Scarlet ...	$0^{\mu}\cdot 65$	66,000000,000000	"	=	1,600000	"
Crimson ..	$0^{\mu}\cdot 75$	33000,000000	"	=	780	"

Stating these values in terms of horse power we have

Minimum Visibile.

		h. p.
Violet	$0^{\mu}\cdot 40$	0·000000,000000,00018000
Green	$0^{\mu}\cdot 55$	0·000000,000000,00000075
Scarlet	$0^{\mu}\cdot 65$	0·000000,000000,00017000
Crimson (near A) ..	$0^{\mu}\cdot 75$	0·000000,000000,34000000

The measurement of the *minimum visibile* is subject to variations of a much wider range than those of the photometric method and may perhaps be in error by 100 per cent.*

* The relative sensitiveness of the eye of the observer in question (F. W. V.) for the extreme red or violet. as compared with its power of detecting green light, appears to be somewhat less when determined by the method of *minimum visibile* than by the reading of fine print.

By the former we have

The probable error of a series of ten readings of fine print, under the actual conditions of observation with a (feeble) standard luminosity, is determined for two of the observers as follows:

	Violet Light $\lambda = 0^{\mu}{\cdot}40$	Orange-yellow light $\lambda = 0^{\mu}{\cdot}60$	Scarlet light $\lambda = 0^{\mu}{\cdot}65$
	Probable Error of one observation.		
	%	%	%
F. W. V.	5·53	1·76	3·14
E. M.	7·69	2·51	2·86
	Probable Error of mean.		
F. W. V.	1·75	0·56	0·99
E. M.	2·44	0·80	0·90

The measurements with violet light were made June 19, 1888, "sky hazy blue, thin but uniform cirrus haze." Those at wave-lengths $0^{\mu}{\cdot}60$ and $0^{\mu}{\cdot}65$ were obtained on June 20, 1888, "sky hazy blue with cumuli, haze not as dense as on the 19th but possibly less uniform."

For a large part of the spectrum the probable error of a single reading does not exceed 4 per cent but the error may considerably exceed this for the violet rays, *the eye requiring a much longer time to regain its sensitiveness for light of this color than for any other*, so that for measures in this region an hour's stay in the darkened room is none too much to develop the full power of an eye which has recently been exposed to the full sunshine.

Time required for Vision.

In connection with the photometric measures the time required for the perception of very faint colored lights was

Sensitiveness violet ($^{\mu}{\cdot}40$) : green ($^{\mu}{\cdot}55$)=1 : 240
" scarlet ($^{\mu}{\cdot}65$) : green ($^{\mu}{\cdot}55$)=1 : 230
" crimson ($^{\mu}{\cdot}75$) : green ($^{\mu}{\cdot}55$)=1 : 450,000

Photometry by the reading of fine print gave for the same observer

Violet, sensitiveness of eye =0·104,000
Green, " " =5·790,000
Scarlet, " " =0·036,000
Crimson, " " =0·000,070

unity being the sensitiveness for yellow light; and the relative effect by this method is

Violet ($^{\mu}{\cdot}40$) : green ($^{\mu}{\cdot}55$)=1 : 56
Scarlet ($^{\mu}{\cdot}65$) : green ($^{\mu}{\cdot}55$)=1 : 160
Crimson ($^{\mu}{\cdot}75$) : green ($^{\mu}{\cdot}55$)=1 : 83,000

investigated. The method was an electrical one. There was automatic registration on a chronograph of the instant of exhibition, and determination of the instant of response as the observer pressed a key. The interval of course includes quite a train of distinct operations. According to Mendenhall (this Journal, III, vol. ii, p. 156), that portion of the action of brain nerve, and muscle which produces the mechanical effect, and which may be called automatic, takes place in certainly but little over one-tenth of a second. But the sensations which demand a conscious concentration of the attention, and especially those which require for their registration a decision of the judgment, occupy an interval several times as great. The perception of a light just at the verge of visibility probably involves an exercise of judgment,—an answer to the question, "Do I see the light or do I not?"—although the question may not be consciously propounded, and accordingly this kind of perception may be included in that class of combined sensation and mental operation which involves a choice. Professor Mendenhall found for the time required to decide between red and white $0^{sec.}\cdot 443$ and to decide between a circle and a triangle $0^{sec.}\cdot 494$. We have found for the average of over 1000 observations of the disappearance or reappearance of a very faint light (perhaps 20 times as bright as the faintest perceptible), $0^{sec.}\cdot 507$, but corresponding measures with a moderately bright spectrum, the light being about 10,000 times as intense as that called "very faint," gave $0^{sec.}\cdot 242$, a number which is intermediate between the times found by Professor Mendenhall for the appearance of a white card ($0^{sec.}\cdot 292$) and that of an electric spark ($0^{sec.}\cdot 203$). We may therefore conclude that distinct vision for a very faint light demands about one-half second of time, while the perception of light of ordinary brightness requires only about half that interval. It is possible that differences in the rapidity of the perception for lights of different colors might be detected on more exhaustive study, but none have been noted in these experiments other than those which were attributable to the variation of intensity.

It will be seen that quantitative measures of the effect upon the eye of different rays whose luminosity varied in the proportion of 200 000 : 1, were actually obtained and that it would have been possible to considerably exceed these limits, especially when it is considered that the photometric measures were confined to lights of feeble intensity. Since it is possible to look directly at the sun for as short a time as one-half second, it is certain that the eye, by the combined adaptability of the iris and retina, can perceive lights whose intensities vary in the ratio of 1 to 1 000 000000 000000.* $(10)^{15}$

* It may be interesting to check this result by an entirely different method. The light of the sun is, according to Pickering, equal to that of a star of $-25{\cdot}5$

It will be understood that the writer does not profess any competence in physiological optics, and that the preceding observations and the conclusions reached from them are both to be understood from the purely physical point of view. This being premised, we will summarize the paper in the following conclusions.

The time required for the distinct perception of an excessively faint light is about one-half second. A relatively very long time is, however, needed for the recovery of sensitiveness after exposure to a bright light, and the time demanded for this restoration of complete visual power appears to be greatest when the light to be perceived is of a violet color.

The visual effect produced by any given, constant amount of energy varies enormously according to the color of the light in question. It varies considerably between eyes which may ordinarily be called normal ones, but an average gives the following proportionate result for seven points in the normal spectrum, whose wave-lengths correspond approximately with those of the ordinary color divisions, where unity is the amount of energy (about $\frac{1}{1000}$ erg) required to make us see light in the crimson of the spectrum near A, and where the six preceding wave-lengths given correspond approximately to the six colors violet, blue, green, yellow, orange, red.

Color.	Violet.	Blue.	Green.	Yellow.	Orange.	Red.	Crims.
Wave-length,	$^{\mu}$·40	$^{\mu}$·47	$^{\mu}$·53	$^{\mu}$·58	$^{\mu}$·60	$^{\mu}$·65	$^{\mu}$·75
Luminosity, (Visual effect.)	1,600	62,000	100,000	28,000	14,000	1200	1

Since we can recognize color still deeper than this crimson, it appears that the same amount of energy may produce *at least* 100,000 times the visual effect in one color of the spectrum that it does in another, and that the *vis viva* of the waves whose length is 0″·75, arrested by the ordinary retina, represents work done in giving rise to the sensation of crimson light of 0·00300000000003 horse power, or about 0·001 of an erg, while the sensation of green can be produced by 0·000000,01 of an erg.

stellar magnitude, or 4400,000000 times that of Sirius (Mag. —1·4) which again is about 910 times that of a sixth magnitude star, ordinarily considered the faintest visible to the naked eye. Here the light of the sun is to that of the *minimum visibile* as 1 to 4,000000,000000 (4×10^{12}), but the difference seems accounted for by the fact that the ratio by this latter method is found for an eye exposed in starlight by the former for an eye in *absolute* darkness.